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An air quality assessment onboard an Oberon class submarine:

HMCS Okanagan

Y.D. Severs
B.H. Sabiston

Defence R&D Canada

Technical Report

DCIEM TR 2000-105

September 2000

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Abstract

Prior to the Canadian Navy's move to the new Victoria class submarine (former RN Upholders), DCIEM was tasked to re-examine the air quality on an Oberon class submarine to determine if the atmosphere complied with Air Purification Standard BR 1326. The objective of the study was to obtain information to assist in developing plans for future submarine air quality management. Since the information would be directly applicable and transferable to the Victoria submarines, the conduct of a trial on an Oberon was warranted. This trial represents a baseline evaluation of submarine air quality under patrol conditions. Over a 24-hour period, the functional and detection capabilities of analytical instruments for monitoring the atmosphere were assessed and a 'fingerprint' of the contaminants onboard was obtained. A profile of Carbon Dioxide (CO_2) accumulation and Oxygen (O_2) consumption was determined and the effectiveness of air purification (CO_2 scrubbing; O_2 generation; and, snorting) was assessed. In addition, Carbon Monoxide (CO) was monitored and Carboxyhemoglobin (COHb) was measured in representative smokers and nonsmokers. Ammonia (NH_4), Ozone (O_3), and Nitrous compounds (NO_x) were measured to assess, respectively, whether the sanitary systems, electrical systems, and engine exhaust gases posed any problems. Hydrogen (H_2), Arsine, and Stibene were monitored to assess any potential hazard from charging the batteries. To assess the health hazard potential of aerosolized particles derived from cooking, smoking, and diesel fuel & exhaust gases, concentrations of respirable airborne particulates were measured. All contaminants covered by BR 1326 were found to be within allowable limits. Respirable particulates are not covered by BR 1326, or by any other Military Standard, and the data were interpreted by applying the Threshold Limit Value/Time Weighted Average (TLV/TWA) civilian occupational health guidelines. The overall TLV/TWA for particulates was within allowable limits. Despite the fact that CO_2 and O_2 concentrations fell within acceptable limits, the study confirmed that air purification measures on diesel submarines are minimal and poorly placed and that there is a lack of exhaust ventilation. Poor to non-existent air exchange was compounded by compartmentalization and blackout curtains; and, contaminant measurement devices (mechanical colorimetric analyzers) were confirmed to have inherent measuring errors. A review of management practices revealed that the adoption of BR 1326, as the sole submarine air purification Standard, had resulted in the loss of replacement schedules for CO_2 canisters and O_2 candles contained in a previous Standard, BR 3944. Moreover, the guidelines to assist Commanders in maintaining air quality in submarines appear to be open to interpretation. Although atmospheric conditions were found to be within specifications, several recommendations are made to enhance the management of submarine air quality in Victoria class submarines.

Résumé

Avant que la Marine canadienne ne commence à utiliser les nouveaux sous-marins de classe Victoria (d'anciens sous-marins de type Upholder de la RN), on a confié à l'IMCME la tâche de réexaminer la qualité de l'air à bord d'un sous-marin de classe Oberon, afin de déterminer si l'atmosphère est conforme à la norme d'épuration de l'air BR 1326. L'objectif de l'étude était de recueillir des renseignements permettant de faciliter l'élaboration de futurs plans de gestion de la qualité de l'air à bord de nouveaux sous-marins. L'exécution d'un essai à bord d'un Oberon est justifiée puisque les renseignements obtenus peuvent être directement appliqués et transférés au cas des sous-marins de classe Victoria. Cet essai correspond à une évaluation de référence de la qualité de l'air d'un sous-marin dans des conditions de patrouille. On a évalué, au cours d'une période de 24 heures, les capacités de fonctionnement et de détection d'instruments d'analyse servant à contrôler l'atmosphère et on a déterminé « l'empreinte chimique » des agents contaminants présents à bord. On a établi un profil de l'accumulation de dioxyde de carbone (CO_2) et de la consommation d'oxygène (O_2) et on a évalué l'efficacité du système d'épuration d'air (épuration du CO_2, production d'O_2 et marche au schnorchel). De plus, on a surveillé la concentration de monoxyde de carbone (CO) et mesuré celle de carboxyhémoglobine (COHb) dans le sang de fumeurs et de non-fumeurs représentatifs. On a mesuré les concentrations d'ammoniac (NH_4), d'ozone (O_3) et de composés azoteux (NO_x) afin de déterminer si ces gaz, associés respectivement aux circuits sanitaires, aux circuits électriques et aux systèmes d'échappement des moteurs, créent des problèmes. On a surveillé la concentration d'hydrogène (H_2), d'arsine et de stibine afin d'évaluer tout danger pouvant résulter de la charge de batteries. Afin d'évaluer les dangers potentiels pour la santé que posent les particules en aérosol provenant de la cuisson, de l'usage du tabac et des gaz d'échappement et de carburant diesel, on a mesuré les concentrations de particules atmosphériques inhalables. Les concentrations de tous les contaminants dont traite la Norme BR 1326 se situent dans les limites acceptables. La Norme BR 1326, ou toute autre Norme militaire, ne traite pas des particules inhalables. L'interprétation des données relatives à ces substances a donc été effectuée en appliquant la valeur limite d'exposition (TLV) et l'exposition moyenne pondérée en fonction du temps (TWA) des lignes directrices civiles en matière de santé professionnelle. Les valeurs globales de TLV et de TWA, pour les particules, se situent dans les limites acceptables. Bien que les concentrations de CO_2 et d'O_2 se situent aussi dans les limites acceptables, l'étude a confirmé que les mesures d'épuration de l'air, dans les sous-marins à propulsion diesel, sont minimales et mal situées et que la capacité de la sortie de ventilation n'est pas suffisante. Le renouvellement d'air est inexistant ou sinon, de qualité médiocre, et le problème est aggravé par la compartimentation et les rideaux d'occultation. On a aussi confirmé que les appareils utilisés pour mesurer la concentration des contaminants (des analyseurs colorimétriques mécaniques) possèdent des erreurs de mesure intrinsèques. L'examen des pratiques de gestion révèle que l'adoption de la Norme BR 1326 comme norme exclusive en matière d'épuration de l'air à bord des sous-marins a entraîné l'élimination des remplacements périodiques de réservoirs filtrants de CO_2 et de bougies filtrantes pour O_2, lesquels faisaient partie d'une norme antérieure (BR 3944). De plus, les lignes directrices visant à aider les Commandants à assurer la qualité de l'air dans les sous-marins semblent être l'objet de différentes interprétations. Bien qu'on ait établi que les conditions atmosphériques se situent

dans les normes, nous proposons plusieurs recommandations visant à améliorer la gestion de la qualité de l'air à bord des sous-marins de classe Victoria.

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Executive summary

To assist in developing plans for future submarine air quality management in the new Victoria class submarines (former Royal Navy (RN) Upholders), DCIEM was tasked to re-examine the air quality on an Oberon class submarine to determine if the atmosphere complied with Air Purification Standard BR 1326. An Oberon habitability trial was warranted on the basis that both the Oberon and Victoria submarines are diesel–powered and have comparable air handling and purification systems. Thus, information gained from a trial onboard an Oberon would be directly applicable and transferable to the Victoria class.

This trial represents a baseline evaluation of submarine air quality under patrol conditions. Over a 24-hour period, the functional and detection capabilities of analytical instruments for monitoring the atmosphere were assessed and a 'fingerprint' of the contaminants onboard was obtained. A profile of Carbon Dioxide (CO_2) accumulation and Oxygen (O_2) consumption was determined and the effectiveness of air purification (CO_2 scrubbing; O_2 generation; and, snorting) was assessed. In addition, Carbon Monoxide (CO) was monitored and Carboxyhemoglobin (COHb) was measured in representative smokers and nonsmokers. Ammonia (NH_4), Ozone (O_3), and Nitrous compounds (NO_x) were measured to assess, respectively, whether the sanitary systems, electrical systems, and engine exhaust gases posed any problems. Hydrogen (H_2), Arsine, and Stibene were monitored to assess any potential hazard from charging the batteries. To assess the health hazard potential of aerosolized particles derived from cooking, smoking, and diesel fuel & exhaust gases, concentrations of respirable airborne particulates were measured.

All contaminants covered by BR 1326 were found to be within allowable limits. Respirable particulates are not covered by BR 1326, or by any other Military Standard, and the data were interpreted by applying the Threshold Limit Value/Time Weighted Average (TLV/TWA) civilian occupational health guidelines. The overall TLV/TWA for particulates was within allowable limits. Despite the fact that CO_2 and O_2 concentrations fell within acceptable limits, the study confirmed that air purification measures on diesel submarines are minimal and poorly placed and that there is a lack of exhaust ventilation. Poor to non-existent air exchange was compounded by compartmentalization and blackout curtains; and, contaminant measurement devices (mechanical colorimetric analyzers) were confirmed to have inherent measuring errors. A review of management practices revealed that the adoption of BR 1326, as the sole submarine air purification Standard, had resulted in the loss of replacement schedules for CO_2 canisters and O_2 candles contained in a previous Standard, BR 3944. Moreover, the guidelines to assist Commanders in maintaining air quality in submarines appear to be open to interpretation.

Although atmospheric conditions were found to be within specifications, one needs to look beyond simple compliance with existing regulations to successfully manage submarine air quality in the future. This is essential to ensure the health and safety of submariners and optimize operational effectiveness. Research initiatives should be continued to assist in guiding the development of a Canadian Submarine Air Quality Standard. In support of this

objective, several recommendations are made to enhance the management of submarine air quality in Victoria class submarines. These include: aggressive attempts to secure RN environmental test reports on the Upholder submarines; a review of all parameters governing the design and use of CO_2 scrubbers, including an analysis of factors to be considered in determining and promulgating schedules for CO_2 canister replacements; an ongoing review of technologies for the accurate and reliable monitoring of contaminants under the harsh environmental conditions onboard a submarine; an assessment of a new CO absorption canister which can be used in existing CO_2 scrubber units; the conduct of engineering feasibility studies to investigate the potential installation of filtering units to decrease particulate and volatile organic materials; the conduct of future research on the chemical composition of aerosolized particulates and the establishment of appropriate particulate guidelines for submarine operations; the establishment of a Materials Toxicity Guide to govern and control materials brought onboard a submarine; the convening of a Working Group of experienced submarine Commanders to harvest their collective experience in interpreting and applying the existing Standard to preserve a habitable submarine environment, and to help shape future submarine air quality management initiatives, under both operational and emergency situations; the conduct of regular air quality assessments of Victoria class submarines operating under worse case (ultra-quiet) scenarios to gain data in support of establishing and maintaining a Canadian submarine habitability guide; and, the conduct of an impact assessment on the potential introduction of an Atmosphere Independent Propulsion (AIP) system and the requirements for an Atmosphere Independent Life Support (AILS) system for preserving an acceptable submarine environment.

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Sommaire

Pour faciliter l'élaboration de futurs plans de gestion de la qualité de l'air à bord des nouveaux sous-marins de classe Victoria (d'anciens sous-marins de type Upholder de la Royal Navy (RN)), on a confié à l'IMCME la tâche de réexaminer la qualité de l'air à bord d'un sous-marin de classe Oberon, afin de déterminer si l'atmosphère est conforme à la Norme d'épuration de l'air BR 1326. L'exécution de l'essai d'habitabilité dans l'Oberon est justifiée puisque les sous-marins de classe Oberon, tout comme ceux de classe Victoria, sont munis de moteurs diesels et qu'ils possèdent des systèmes semblables de distribution et d'épuration de l'air. On pourrait ainsi appliquer et transférer directement les renseignements obtenus lors d'un essai à bord d'un Oberon à un sous-marin de classe Victoria.

Cet essai correspond à une évaluation de référence de la qualité de l'air d'un sous-marin dans des conditions de patrouille. On a évalué, au cours d'une période de 24 heures, les capacités de fonctionnement et de détection d'instruments d'analyse servant à contrôler l'atmosphère et on a déterminé « l'empreinte chimique » des agents contaminants présents à bord. On a établi un profil de l'accumulation de dioxyde de carbone (CO_2) et de la consommation d'oxygène (O_2) et on a évalué l'efficacité du système d'épuration d'air (épuration du CO_2, production d'O_2 et marche au schnorchel). De plus, on a surveillé la concentration de monoxyde de carbone (CO) et mesuré celle de carboxyhémoglobine (COHb) dans le sang de fumeurs et de non-fumeurs représentatifs. On a mesuré les concentrations d'ammoniac (NH_4), d'ozone (O_3) et de composés azoteux (NO_x) afin de déterminer si ces gaz, associés respectivement aux circuits sanitaires, aux circuits électriques et aux systèmes d'échappement des moteurs, créent des problèmes. On a surveillé la concentration d'hydrogène (H_2), d'arsine et de stibine afin d'évaluer tout danger pouvant résulter de la charge de batteries. Afin d'évaluer les dangers potentiels pour la santé que posent les particules en aérosol provenant de la cuisson, de l'usage du tabac et des gaz d'échappement et de carburant diesel, on a mesuré les concentrations de particules atmosphériques inhalables.

Les concentrations de tous les contaminants dont traite la Norme BR 1326 se situent dans les limites acceptables. La Norme BR 1326, ou toute autre Norme militaire, ne traite pas des particules inhalables. L'interprétation des données relatives à ces substances a donc été effectuée en appliquant la valeur limite d'exposition (TLV) et l'exposition moyenne pondérée en fonction du temps (TWA) des lignes directrices civiles en matière de santé professionnelle. Les valeurs globales de TLV et de TWA, pour les particules, se situent dans les limites acceptables. Bien que les concentrations de CO_2 et d'O_2 se situent aussi dans les limites acceptables, l'étude a confirmé que les mesures d'épuration de l'air, dans les sous-marins à propulsion diesel, sont minimales et mal situées et que la capacité de la sortie de ventilation n'est pas suffisante. Le renouvellement d'air est inexistant ou sinon, de qualité médiocre, et le problème est aggravé par la compartimentation et les rideaux d'occultation. On a aussi

confirmé que les appareils utilisés pour mesurer la concentration des contaminants (des analyseurs colorimétriques mécaniques) possèdent des erreurs de mesure intrinsèques. L'examen des pratiques de gestion révèle que l'adoption de la Norme BR 1326 comme norme exclusive en matière d'épuration de l'air à bord des sous-marins a entraîné l'élimination des

remplacements périodiques de réservoirs filtrants de CO_2 et de bougies filtrantes pour O_2, lesquels faisaient partie d'une norme antérieure (BR 3944). De plus, les lignes directrices visant à aider les Commandants à assurer la qualité de l'air dans les sous-marins semblent être l'objet de différentes interprétations.

Bien qu'on ait établi que les conditions atmosphériques se situent dans les normes, il faut dépasser le simple respect des règlements existants si on veut, à l'avenir, gérer avec succès la qualité de l'air à bord des sous-marins. C'est un élément essentiel pour assurer la santé et la sécurité des sous-mariniers et optimiser l'efficacité opérationnelle. Les initiatives de recherche doivent se poursuivre afin de faciliter l'élaboration d'une Norme canadienne de la qualité de l'air à bord des sous-marins. Pour atteindre cet objectif, nous proposons plusieurs recommandations visant à améliorer la gestion de la qualité de l'air à bord de sous-marins de classe Victoria. Ces recommandations comprennent : des efforts énergiques pour se procurer les rapports sur les essais en milieu ambiant effectués par la RN dans les sous-marins de type Upholder; l'examen de tous les paramètres régissant la conception et l'utilisation de systèmes d'épuration de CO_2, dont l'analyse des facteurs dont on doit tenir compte lorsqu'on établit et met en place les plans de remplacement des réservoirs filtrants de CO_2; l'examen continu des techniques permettant le contrôle précis et fiable des contaminants dans les conditions rigoureuses propres au milieu d'un sous-marin; l'évaluation d'un nouveau réservoir filtrant de CO qui peut être utilisé dans les systèmes existants d'épuration de CO_2; l'exécution d'études de faisabilité technique, afin d'évaluer l'installation éventuelle de filtres pour réduire les quantités de particules et de composés organiques volatils; la réalisation de futurs travaux de recherche portant sur la composition chimique des particules en aérosol et la détermination de lignes directrices appropriées en matière de particules présentes lors d'opérations à bord de sous-marins; la création d'un guide de la toxicité des substances permettant de réglementer et de contrôler les matières apportées à bord d'un sous-marin; la réunion d'un groupe de travail, composé de Commandants de sous-marin expérimentés, pour recueillir leur expérience collective relative à l'interprétation et l'application de la Norme existante qui assure un milieu habitable dans les sous-marins et pour faciliter l'élaboration de futures initiatives en matière de gestion de la qualité de l'air à bord des sous-marins, en situation opérationnelle comme en situation d'urgence; l'exécution d'évaluations régulières de la qualité de l'air dans les sous-marins de classe Victoria évoluant dans le pire scénario (sous-marin ultra-silencieux), afin de recueillir des données pouvant renforcer la mise en place et le maintien d'un guide canadien sur l'habitabilité des sous-marins et finalement, la réalisation d'une étude d'évaluation des impacts portant sur l'introduction éventuelle d'un système de propulsion indépendant de l'atmosphère (AIP) et sur les exigences associées à un système de survie indépendant de l'atmosphère (AILS) permettant d'assurer un milieu acceptable dans les sous-marins.

Severs, Y.D.; Sabiston, B.H. 2000. An air quality assessment onboard an Oberon class submarine: HMCS Okanagan. DCIEM TR 2000-105. Defence and Civil Institute of Environmental Medicine.

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Sincerest thanks are extended to the Commanding Officer and crew of HMCS Okanagan. Their willingness to provide any and all technical support required, and their eagerness to educate the team on the configuration and procedures of the submarine, ensured that the study reflected the true air quality conditions onboard a submarine. Their support and kindness made the transition into this unique environment much easier. Even though the members of the DCIEM team were not submariners, they were welcomed by, and made to feel part of the crew.

Sincerest thanks and acknowledgement must go to the DCIEM Preventive Medicine technicians, Sgt. Brad Jordan and MCpl. Mark Switzer. Their significant technical contributions; commitment of time; and, unyielding efforts before, during, and upon completion of the trial, were outstanding. Their motivation and insightful suggestions made a very demanding and complicated study go smoothly.

Objective

At the request of Maritime Forces Atlantic (MARLANT) Headquarters, the DCIEM Health Hazards Group (HHG) was tasked by Director General Maritime Development and Operations/Director Policy and Project Development (DGMDO/DMPPD) to re-evaluate the habitability of Canada's patrol submarines in order to re-affirm their compliance with the current permissible contaminant limits stipulated in Air Purification Standard BR 1326 [1].

In order to fulfil the requirements of the tasking, three key objectives were identified:

a. to identify and quantify contaminants found under all operational scenarios;

b. to verify compliance with, and if necessary, update the toxic substance list of Standard BR 1326;

c. to provide engineering or procedural recommendations for improving health and safety while ensuring operational capability and effectiveness.

Operational requirements, and historical limitations in air-monitoring instrumentation, dictated that the achievement of the objectives be performed in phases. This report addresses Phase 1, a baseline air quality study performed 4-5 August 1998, onboard HMCS Okanagan. The purpose of Phase 1 was to assess analytical instrument functionality and detection capability under a worse case environmental scenario and to obtain a fingerprint of the contaminants present onboard the submarine, in preparation for further detailed study.

The overall intent of this, and future submarine habitability studies, is to provide the Navy with information and guidance of air quality onboard diesel submarines to:

a. assist operational managers in:

   (i) maintaining an acceptable atmospheric quality onboard submarines;
   (ii) developing and maintaining a reliable atmosphere-monitoring policy;
   (iii) establishing a submarine smoking policy;
   (iv) developing smoke clearance procedures;

b. provide the medical community with an atmospheric snapshot of the submarine environment; and,

c. provide recommendations for reliable and accurate atmospheric monitoring equipment.

Introduction

In January 1998, a MARLANT Headquarters review of management initiatives for submarine air quality [2] suggested that it would be desirable to re-examine the topic of air quality to determine if the overall atmosphere in Canadian Navy submarines continued to comply with the requirements of Air Purification Standard BR1326 [1]. This Standard is a Royal Navy (RN) publication, adopted by the Canadian Forces (CF).

Several engineering modifications, and alterations to atmosphere-purification and sampling protocols, had been implemented in Canadian submarines since the last habitability assessment of 1987 [3]. It was deemed appropriate, therefore, to assess the effectiveness of these changes on ventilation and air quality in the context of submariner health and safety; permissible concentrations of toxic and explosive substances set within Standard BR 1326; and, technological advances in instrumentation for monitoring contaminants in the environment. It was expected that the results of the evaluation would permit a valid and accurate review of the maximum permissible concentrations of toxic and explosive substances found in Standard BR 1326 and, if necessary, a basis for updating the listed contaminants and their maximum permissible exposure concentrations (MPC).

With the announcement of Canada's purchase and ensuing acceptance of the British Upholder class submarines (subsequently designated the Victoria class), the value of conducting a baseline habitability study on an Oberon boat was re-examined. Given the following facts, it was concluded that a habitability trial on an Oberon was warranted, since the information gained would be directly applicable and transferable to the Victoria class submarines:

- both the Oberon's and the Victoria's are diesel operated;
- the method of cleansing and upgrading the atmosphere is identical, i.e. Oxygen (O_2) candles and Carbon Dioxide (CO_2) scrubbers;
- the relative position of O_2 candles and CO_2 scrubbers is the same, i.e. fore and aft compartments; and,
- the mission operations and Oberon Standard Operating Procedures (SOPs) would be migrated to the Victoria boats.

A plan was then implemented, whereby the submarine air quality project was divided into phases. This study, a baseline assessment of an Oberon class submarine, constitutes Phase 1. This was to have been followed up by an in-depth habitability study on at least one other Oberon boat before receipt of the first Victoria class submarine. Due to the assignment of the authors to other duties, the latter habitability study was not implemented. The long-term plan, however, is to conduct an extensive air quality assessment onboard the first Victoria boat, once she arrives in Canada and, thereafter, to monitor conditions, periodically, on other submarines as they enter service [4].

The overall objective of this, and future submarine habitability studies, is to provide the Navy with information and guidance for air quality management onboard diesel submarines to:

a. assist operational managers in:

   (i) maintaining an acceptable atmospheric quality onboard submarines;
   (ii) developing and maintaining a reliable atmosphere-monitoring policy;
   (iii) establishing a submarine smoking policy;
   (iv) developing smoke clearance procedures;

b. provide the medical community with an atmospheric snapshot of the submarine environment; and,

c. provide recommendations for reliable and accurate atmospheric monitoring equipment.

Historically, monitoring atmospheric conditions within a diesel submarine has been fraught with technical difficulties. This is because of the prevailing harsh environmental conditions, which interfere with electronic analytical instrumentation. These conditions include: sudden pressure differentials; condensing water vapour; relatively extreme temperature changes (50C - 400C); presence of potentially interfering contaminants, eg. Hydrogen (H_2) gas affecting accurate reading of Carbon Monoxide (CO) levels; and, the concurrent presence of particulate dust and aerosols, fumes, and vapors. Because of these factors, a considerable degree of uncertainty surrounds the accurate and reliable monitoring of atmospheric contaminants. For this reason, it was deemed prudent and relevant to design a habitability trial to first confirm the reliability of any analytical instrumentation and, ideally, to do so under a worse case operational scenario. Conducting a trial under a worse case scenario would have the added benefit of providing data which could be analyzed and interpreted to permit both an assessment of air quality degradation within the submarine, and a critical and valid appraisal of the MPC, defined within Standard BR 1326.

A worse case scenario was defined as 24 hours submergence. Collecting data over this time period would effectively provide a snapshot of submariner exposure to all atmospheric contaminants and this, in turn, would enable one to assess any potentially compromising health effects. Awareness of the health effects of both acute and chronic exposures would also assist in evaluating any apparent degradation in performance, both immediate and long-term. Any degradation in performance could adversely affect operational capability. Thus, collection of accurate data of the atmospheric conditions onboard the submarine was deemed essential in providing information needed to corroborate current policies and procedures dealing with the management of submarine air quality and, if necessary, to substantiate any recommendations for improving existing SOPs to prevent any potential reduction in operational capability due to submariner exposure to atmospheric contaminants.

Methods

Test protocol

This study was conducted onboard HMCS Okanagan during the period 4-5 August 1998, while Okanagon undertook sea training exercises. Originally, it had been planned to carry out the study during full operational exercises in order to assess habitability under worse case non-snort conditions. Because of sea-training exercises, full environmental monitoring could not begin until all exercises which introduced foreign contaminants to the environment were completed, and the contaminants had been cleared, e.g. the smoke from smoke bombs during simulated fire exercises. Notwithstanding this limitation, when full environmental monitoring was begun, patrol conditions were achieved over a continuous 16.5-hour period and the objectives of the study were achieved successfully. The objectives were to assess the functionality and detection capability of air monitoring instrumentation and to identify and quantify atmospheric contaminants under patrol conditions.

In order to assess air quality compliance with Standard BR 1326, the protocol was designed to monitor conditions while maintaining routine operational procedures and standard policies as predetermined by the submarine squadron, MAROPSGRU5. Throughout the trial, all routine submarine air quality procedures and policies were maintained. These included the air purification initiation and replacement schedules and Draeger monitoring of selected contaminants (CO, CO_2, O2) which were taken and recorded by the on-watch Naval Radio Operator. The logged data, obtained and recorded periodically, were later reviewed and compared with the instrument data, recorded continuously and on-line. In general, taking into account the inherent error in Draeger tube monitoring, there was good congruence between the instrument and Draeger tube data.

As mentioned above, continuous monitoring under patrol conditions was achieved over a 16.5-hour period. This enabled a reasonable assessment of the air purification capabilities, routine housekeeping procedures (cleaning and cooking), and lifestyle effects (smoking). Monitoring was continued during the two-hour snort period to observe and document the effectiveness of snorting, the resulting air exchange, and the effects of battery charging.

Sampling and analytical protocol

The compounds selected for measurement during this study were those which are potentially life threatening or carry a risk of producing long-term chronic symptoms. Because allowable exposure limits to these compounds are documented in Standard BR 1326, their measurement also permitted an assessment of compliance with the Standard.

The following air constituents or contaminants were monitored:

- Carbon Monoxide (CO);
- Carbon Dioxide (CO_2);

- Oxygen (O_2);
- airborne respirable particulates;
- Arsine; Stibine; and, Diesel organic compounds;
- Hydrogen (H_2); Ammonia (NH_4); Ozone (O_3); and, Nitrous Fumes (NO_x).

These compounds were monitored using real-time electronic instrumentation, colorimetric tubes, and grab samples. As well, biological uptake of CO was measured by Carboxyhemoglobin (COHb). Relative Humidity and Temperature readings were recorded regularly during the trial.

Real-time monitoring

Routine air constituents

O_2, CO_2 and CO levels within the submarine were continuously monitored in real-time with the following instrumentation:

- Servomex Model 570 Paramagnetic O_2 analyzer, with a maximum detection capability of 100 %;
- Servomex ADC Infrared (IR) CO_2 analyzer, with a maximum detection capability of 5 %;
- Siemens Ultramat 21 CO IR analyzer, with a maximum detection capability of 500 parts per million (ppm);

In addition, a Guardian Plus Model D400 IR CO_2 analyzer (Edinburgh Sensors Ltd., Livingston, England), with a maximum detection capability of 100%, was placed in the Fore Ends of the boat. The purpose of this was to determine its detection capability and accuracy and to assess its utility as a real-time CO_2 analyzer for potential installation in submarines.

Using certified gas standards, three-point calibration curves were performed on all instruments during several phases of the study: prior to the survey; midway into the dive; post-dive; pre-snort; and, upon completion of snort.

Individual CO, CO_2, and O_2 analyzers were located in the Fore Ends of the boat. Separate lines of ¼" O.D. polyethylene tubing were run from the vacuum pumps in each instrument to the "breathing zone" region of four compartments of the boat:

- Fore Ends (foreword of bulkhead 34);
- Accommodation Space (aft of bulkhead 34, Senior Rates Mess);

- Control Room (midship, forward of periscope);
- After Ends (Junior Rates Mess).

Air was drawn from each of these compartments through the polyethylene tubing to the analytical instruments. Sampling of the four areas was achieved by introducing a switching valve (#40 series, Swagelok, Whitney Co., Highland Heights, Ohio) for each of the instruments. This switching valve allowed cyclical 15-minute sampling of air constituents in each compartment during the entire dive period. During the snort period, the cyclical switching was increased to approximately every three minutes.

All air constituent data were continuously collected through a datalogger (DT 100 Datataker, Data Electronics, Boronia, Australia) onto an IBM Think Pad laptop computer (IBM, de Mexico, SA) and stored for analysis.

Airborne particulates

Inhalable airborne particulate concentrations (<10 micron diameter) were measured and stored in real-time using an aerosol particulate monitor (Data Ram, Monitoring Instruments for the Environment Inc., Bedford, Massachusetts).

The total concentration of inhalable particulates was measured in the following areas and for the following periods of time:

- Engine Room & Controller's workstation: 7 hours;
- Motor Room and near the ladder to the lower motor room: 3 hours and 48 minutes;
- Control Room, on the navigation table: 13 hours.

Long-term monitoring

Arsine and Stibene

Arsine and Stibine, potentially produced as a result of battery off-gassing, were collected on adsorption tubes. Charcoal tubes were used for Arsine, and mercuric chloride-impregnated silica gel tubes, were used for Stibene.

The adsorption tubes were fitted to Dupont P4LC air-sampling pumps (Dupont Co., Instruments Systems, Kennett Square, Pennsylvania) calibrated to 30 ml. per minute. All pumps were pre- and post-calibrated on-site using a Kurz Model 540S flow meter (Kurz Instruments Inc. Monterey, California).

Four-hour samples were collected during the battery charging period. These samples were taken from the Battery Compartment (below the galley, 10 feet forward of the hatch); the Engine Room (Battery Compartment exhaust vent); and, the Galley (above the Galley sink).

To ensure accuracy of sampling (i.e. to ensure no external contamination), two "travel blanks" and a four-hour baseline sample from the jetty, collected prior to sailing, were taken on each collection medium. Tubes were subsequently forwarded to the contract laboratory and analyzed: Arsine by Atomic Absorption using NIOSH Method 6001, Issue 2-8/15/94 [5] and Stibine, Spectrophotometrically using NIOSH Method 6008, Issue 2- 8/15/94 [5].

Diesel compounds

To provide a fingerprint of the diesel compounds present onboard the submarine (not knowing specific compounds or concentrations), samples were collected on both Thermal Desorption (TD) and Charcoal tubes. Knowing that benzene is a component of diesel exhaust and that it was likely to be present in the highest concentration and have the highest break-through, the collection times for each of the tubes was based on the benzene break-through time. Thus, the collection time for each of the TD tubes was three hours; that for the charcoal tubes, four hours. Samples were collected over a total 20-hour period.

Using the Dupont P4LC air sampling pumps as described above (i.e. 30 ml per minute flow rate and pre- and post-calibrated), ambient air was drawn from the Engine Room (Engine Room controller's workstation); Control Room (chart table); Fore Ends (forward of bulkhead 34); and, the Galley (above sink).

All tubes were forwarded to the contract laboratory and analyzed using Gas Chromatography (GC), Flame Ionization Detection (FID) using NIOSH Method 1501, Issue 2 - 8/15/94 [5].

Direct reading colorimetric tube monitoring

Ammonia, ozone and nitrous fumes

NH_4, O_3 and Nitrous fumes (NO_2, NO, N_2O) were measured at potential generation sites using Draeger colorimetric tubes (Draeger Canada Ltd., Mississauga, On). NH_4 samples were taken in the Control Room (aft of bulkhead 77); the Heads; and, at the edge of the Galley (forward of bulkhead 49). O_3 samples were taken in the Control Room (aft of bulkhead 49 and foreword of bulkhead 77) and below in the Radar Room. Nitrous fume samples were taken in the Engine Room (near the operators' workstation); the Control Room (near the chart table); and, the Accommodation Space (just forward of bulkhead 49).

For all samples, atmospheric air from the submarine was drawn through each tube using a Draeger bellows-type volumetric pump. Air volumes were dependent upon the readability range and specificity of each tube as outlined in the instructions supplied with each tube. For example, sampling for NH_4 required 10 complete pump actions for tubes CH 20501 in the measurement range of 5 to 70 ppm. The O_3 tube 6733181 also required 10 complete pump actions to measure concentrations in the 0.05 to 0.7 ppm range. On the other hand, NO_x fumes

required only 5 complete pump actions to measure within the 0.5 to 10 ppm range on tubes CH 2940.

It should be appreciated that the inherent analytical error for Draeger tubes can be as high as ± 25%, assuming there is no additional technical or human error or any environmental cross-sensitivity. Despite the inaccuracy of the Draeger tube method, it is the standard method for monitoring contaminants in the diesel submarines and thus it was prudent to include its use during this survey. Samples for all gases were taken prior to sailing; upon diving; every four hours while submerged; pre-snort; and, post-snort.

Grab sampling

Hydrogen gas

Grab samples for H_2 concentrations, generated during battery off-gassing, were collected with 12 cm^3 Bistable Gas samplers (Chemical Products Ltd., Rexdale, ON). Sample collection was initiated at the fully charged state of the batteries and was continued every 15 minutes for one hour. A final sample was taken two hours after charging. Representative sampling was taken just below the forward battery compartment hatch; the Engine Room vent port; Control Room; and, Accommodation Space. Samples were forwarded to the contract laboratory and analyzed by Gas Chromatography/Mass Spectrometry (GC/MS).

Temperature and relative humidity

Relative Humidity readings were recorded periodically during the dive period and once during the snort period (Sling Psychrometer-Bacharach Instruments, Pittsburgh, PA). The areas monitored were the Galley (near the sink area); Engine Room (operator's area); and, the Accommodation Space (aft of bulkhead 34). Temperature was checked and recorded every two hours by the submarine crew in the Fore Ends, Control Room, and After Ends. All readings were taken with a thermometer.

Biological monitoring

Carboxyhemoglobin

The body burden accumulation of CO was measured non-invasively by testing expired CO concentrations in exhaled breath from representative volunteer crewmembers (10 smokers and 10 non-smokers). The CO concentrations were then used to calculate Carboxyhemoglobin (COHb) levels.

To ensure an accurate estimate of the total body burden of CO, COHb concentrations were determined on each volunteer before sailing; approximately every four hours during the dive; immediately prior to snorting; and, on completion of the trial. Each volunteer was supplied with his own collection bag which was evacuated and purged with Nitrogen (N_2) after each

and every use. Timings of samples were adjusted to coincide with work and sleep schedules; therefore not all samples were taken simultaneously.

To ensure the collection of deep lung samples (i.e. alveolar air samples), individuals were instructed to take three deep breaths and hold the third breath for a minimum of 15 seconds. The first half of the breath was then exhaled into the environment; the last half blown into the collection bag. The bag was then clamped.

Breath samples were analyzed immediately using a Siemens Ultramat 21 CO Infrared analyzer, ranging from 0 – 100 ppm (Siemens A.G., Karlsruhe, Germany). The analyzer was calibrated by completing a three-point curve, using certified gas standards. The concentration of CO present was then converted to COHb using the following formula: COHb %= 0.16 X CO ppm.

Statistical analysis

All collected data were reviewed, adjusted for baseline variations, collated and plotted. To determine overall exposure to specific air constituents or contaminants in which continuous real-time data were collected, the "area under the curve" was computed for each area over the time period monitored. Linear regression was performed on CO_2 data for each area to determine the increase in concentration over time.

Results and discussion

The total dive period, which began at 1410 hours on 4 August 1998, was 21 hours and 48 minutes. Upon diving, training exercises were initiated. By 1748 hours, those training exercises that could artificially alter the submarine environment had been completed. At this point, the submarine assumed the non-snort patrol state and all instruments for monitoring the environment were activated and calibrated. Air quality monitoring was initiated at 1915 hours and continued until 1118 hours the following morning.

Variation in CO_2 concentration

Changes in CO_2 concentration in the four main compartments of the boat were monitored continuously for 16 hours and 40 minutes (Figure 1).

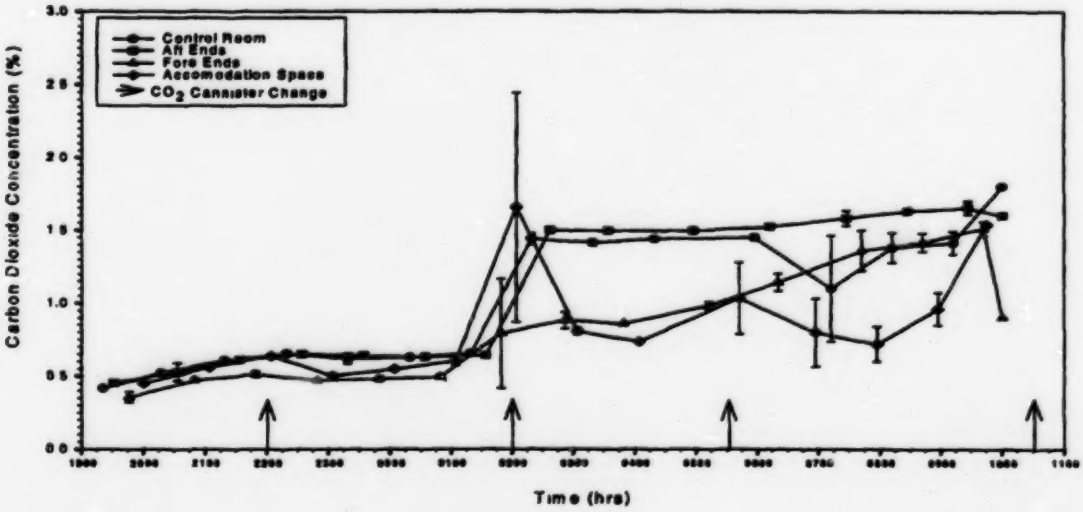

Figure 1. Changes in CO_2 concentration and the effects of air purification scrubbing during patrol state conditions. CO_2 canisters were activated simultaneously in both Fore and After Ends: two canisters at 2145 hours and 0150 hours; four canisters at 0548 hours and 1040 hours, respectively.

Baseline values indicated that the initial CO_2 concentration in each of the four areas ranged from 0.36% in the Fore Ends, through 0.42% in the Control Room, to 0.45% in the After Ends and Accommodation Space. These values are approximately 10 times higher than one would

expect to find in ambient air, which has a CO_2 concentration of approximately 0.04%. This apparent discrepancy can be explained by the fact that the baseline values are actually values determined in a confined space some four hours and 45 minutes after the dive commenced. Thus, they are not ambient air baseline values. Rather, they are baseline values for the start of the air monitoring protocol. They reflect primarily the CO_2 accumulation from crew respiration over the four hour and 45 minute submergence period.

It is interesting to note, however, that two Clearance Snorts, one hour and 30 minutes apart and for durations of 25 minutes and one hour respectively, had been made prior to the start of the air monitoring protocol. Standard BR 1326 suggests that a 35-minute snort will effectively clear the submarine atmosphere. Clearly, the snort procedure on this trial did not completely replenish the atmosphere to ambient conditions. This discrepancy, between what is suggested in the Standard and what actually occurs during operations, underscores the need to re-examine both the Standard and the existing snort procedures.

During the initial six hours of the dive, the CO_2 levels increased gradually and equally in all four monitored areas, but remained within specifications. Approximately 12 hours into the dive, a sudden increase in CO_2 levels was observed in the Control Room, (0.67% to 1.44 %); After Ends (0.64% to 1.5 %); and, in the Accommodation Space (0.6% to 1.66 %). A more gradual increase was observed in the Fore Ends (0.79% to 0.88%).

Standard BR1326 predicts that a CO_2 concentration of 1% will be reached in 4.2 hours *if the initial CO_2 concentration is 0.2% and there is no air purification.* This calculation is based on an average respiration rate of 24L/man/hour; the total volume of the submarine (34,149 ft^3); and, the number of personnel onboard.

On this patrol, two CO_2 canisters were activated, fore and aft, approximately four hours after the last snort. These canisters were activated *before* a 1% CO_2 concentration was attained, i.e. at a concentration of 0.5% as determined by the standard Draeger tube method. It is assumed that the 'early' activation of CO_2 canisters was intended to deter a rise in CO_2 levels. In reality, CO_2 levels were not reduced significantly but the subsequent *rate* of accumulation of CO_2 was reduced.

This period of the study afforded an opportunity to compare readings from the real-time IR CO_2 monitor with those obtained from the manually operated Draeger tube, used operationally. The IR monitor consistently gave readings of CO_2 which were approximately 20% higher than those measured with the Draeger tube. While this difference in readings between the two technologies is not unexpected (i.e. Draeger tube detection is known to have an inherent error of $\pm$ 25%), it does suggest that the Draeger tube technology tends to *underestimate* the prevailing CO_2 concentration.

Figure 1 indicates that there was a sudden and pronounced rise in CO_2 concentration at 0200 hours. This is an anomaly associated with instrument re-calibration and is not operationally relevant. The anomaly has been noted in previous studies [3, 6] and can be attributed to the atmospheric conditions within the confined space onboard a submarine (e.g. temperature, humidity etc.) which are 'unfriendly' to electronic instrumentation. In spite of this anomaly (since data were collected continuously in real-time and the anomaly could be corrected for) it

was possible to analyze the increases in CO_2 concentration, over time, and the impact of air purification.

Regression analysis indicated, that over the dive period, CO_2 concentrations increased: 1327 ppm/hr in the After Ends (R= .84); 1004 ppm/hr in the Fore Ends (R= .82); 1158 ppm/hr in the Control Room (R= .77); and, 639 ppm/hr in the Accommodation Space (R= .32). The regression co-efficient (R-value) suggests that the linear increase in CO_2 concentration is strongly time-related, with the exception of the Accommodation Space.

A comparison of the increases in CO_2 concentration during this study, with those observed previously on HMCS Okanagan [3], indicated that the overall increases were well below those found during the previous trial. This is not surprising, since the CO_2 canister-activation profile was distinctly different. On the current trial, CO_2 canister-activation commenced three hours and 58 minutes into the dive, at a CO_2 concentration well below that demanded by Standard BR1326. There is nothing wrong with this, other than CO_2 canisters are used unnecessarily to preserve the atmosphere. Based upon the CO_2 concentrations observed on this trial, and their rate of accumulation, CO_2 canister-activation could have been delayed until 10.5 hours into the dive, at which point the CO_2 concentration reached an average of 1.72%.

Regardless of the differences between the two trials, the important message is that CO_2 canister-activation, in itself, has very little to no effect in reducing CO_2 concentrations in the Control Room.

The placement of the absorption devices (fore and aft), and the ineffectiveness of the ventilation system in Oberon submarines, nullify the ability of the CO_2 canisters to reduce CO_2 concentrations, especially while Blackout Curtains are in place. The effect of Blackout Curtains, in reducing the effectiveness of CO_2 canisters, can be seen in Figure 1 where, at 0600 hours, the Blackout Curtains were opened briefly and the CO_2 concentration in the Control Room dropped from 1.45% to 1.1% within an hour.

The ineffectiveness of CO_2 absorption units is also demonstrated in the data collected from other compartments. For example, the greatest increase per hour in CO_2 concentration was observed in the After Ends. Even with continual replacement of canisters, CO_2 concentrations continued to rise. A multitude of factors, taken together, contribute to the ineffectiveness of the absorption units:

- configuration of the After Ends (compartmentalized Junior Rates Mess with isolated racks);
- ventilation supply that does not reach into the living quarters;
- poor to non-existent air exchange;
- canisters placed just aft of bulkhead 103, and;
- the large number of occupants (i.e. 22 personnel).

It should be noted, that even when both axial fans are running and there is a perception of a cooling air flow, there is very little effect on the circulation and dilution of CO_2 in the After Ends. The CO_2 concentrations reached 1.5% at 0230 hours (~ 10 hours dived) and continued to increase, peaking at 1.65% at 1030 hours.

The effectiveness of CO_2 canister-activation was a little more evident in the Accommodation Space (i.e. in the Senior Rates Mess). With each canister-activation, CO_2 was reduced (0.64 to 0.5%; 1.66 to 0.81%; and 1.03 to 0.8%, respectively).

While one would think that the Fore Ends would benefit substantially from CO_2 canister-activation (since CO_2 absorption units are placed in the Fore Ends), this is not the case. The Accommodation Space benefited the most, followed by the Control Room (Figure 1). Ironically, the Fore Ends and the After Ends benefited little.

Again, this may be due to multiple factors:

- the placement of the CO_2 absorption units just forward of bulkhead 34;
- the supply ventilation trunk reaching only just forward of bulkhead 34;
- the non-existent exhaust ventilation from the compartment.

It should be noted that purified air is not recirculated. Instead, air within each compartment is continually redrawn into the absorption units and this may lead to a saturation of the absorbent and a decrease in its efficiency. This is not to say that the canisters have no effect at all. In the Fore Ends, for example, the open concept allows for a somewhat natural dilution and so, while an actual decrease in CO_2 concentration was not observed, there was a slower rise in CO_2, over time.

The results of this trial have indicated that air quality can be maintained within specifications during patrol state conditions by activating CO_2 canisters every four hours (two canisters (x 2) initially, then four (x 2). This is clearly shown by the data in Figure 1 where a maximal increase of 1.45% of CO_2 in the Control Room; 1.65% in the After Ends; 1.51% in the Fore Ends; and, 1.65% in the Accommodation Space, is shown. Clearly, the recommended upper limit of 1.75% CO_2 (see Reference 1) was not exceeded.

The application of a 1.75 % limit is based upon criteria specified in the notes of Standard BR 1326 which state that an upper limit exposure of 1.75% is permissible, *if* daily ventilation is carried out. However, in the absence of daily ventilation, the MPC drops to 1% [1].

Although this study monitored the environment under patrol state conditions and the results indicate that air quality was within specifications, the results cannot be attributed to the operational guidelines for air purification set out in Standard BR 1326. The Standard unfortunately does not provide a suggested canister replacement schedule to maintain CO_2 levels within permissible limits. Assistance is only provided in the form of the expected time CO_2 concentrations of 1%, 2%, and 3% will be reached with a crew of 70, 80, or 90 men, respectively. It would be helpful if the Standard included formulae for calculating canister replacements, based upon crew size, level of work or physical activity, compartment size, and

ventilation airflow. As it stands, the Standard does not indicate when canister activation should be initiated, how many should be used at any one time, or how often the canisters should be changed. No guidance is provided as to how best to use the limited number of CO_2 canisters that are available. A previously used Standard, BR 3944, *Air Purification in Patrol Class Submarines* [7] did provide a suggested canister replacement schedule. The use of this Standard was discontinued in 1989 because interpretation of the replacement schedules was confusing and because the underlying calculations for determining canister replacements were suspect.

The problem of calculating canister replacement schedules is not new. As early as 1981, in a report to the Flag Officer Submarines Royal Navy [8], Nimmo-Scott noted the confusion surrounding submarine air-quality guidelines and suggested strongly that the MPC and calculations governing canister replacement schedules be reviewed. This has not yet occurred. In the absence of objective guidelines for calculating CO_2 canister replacement schedules, submarine crews must continue to rely on inaccurate data (i.e. Draeger tube measurements) and past memory and experience (i.e. corporate history). Neither of these parameters is objective, consistent, or reliable.

On this trial, early activation of CO_2 canisters clearly helped to reduce the rate of CO_2 accumulation. At face value, there is nothing wrong with the practice of activating CO_2 canisters at CO_2 concentrations lower than those called for in the Standard. However, the practice does consume canisters at an accelerated rate and this could become an operationally limiting factor, especially under prolonged submergence conditions. To place this in perspective, had the current trial demanded a 36 hour submergence period (not an unrealistic requirement during operations) and had the CO_2 canister replacement schedule been maintained, a total of 64 CO_2 canisters would have been used. Under these conditions, and without snorting, it would only be possible to carry out two submerged operations. Thereafter, the submarine would have to be re-supplied with CO_2 canisters. The question arises: "How likely is it that the submarine will be able to be re-supplied at sea, routinely or reliably?" The answer to this question is beyond the scope of this paper but the problem it addresses must be considered in any re-formulation of Canada's submarine air quality policies and procedures.

Clearly, without objective guidelines, Commanding Officers are placed in an awkward position of having to decide whether or not to allow CO_2 concentrations to rise above specifications in operational situations where snorting is undesirable or impractical. Their decisions must take into account the logistics associated with the requirements of atmosphere replenishment. The fact is that storage space is at a premium onboard a submarine and there is only so much space allotted for soda-lime canisters.

To make the most efficient use of the 132 canisters available for routine use, it is crucial that Nimmo-Scott's recommendations [8] be re-examined to see if new canister re-placement schedules can be provided. DCIEM's Experimental Diving Unit is currently applying mathematical modeling to see if more efficient replacement schedules can be calculated. The model used takes into account submarine volume, crew size, CO_2 accumulation, scrubber capacity and CO_2 breakthrough, etc. To date, the calculations reveal that the model can reliably simulate conditions measured in submarines. Based upon the model, current scrubber efficiency is calculated to be about 65%. This would appear to be the maximum efficiency achievable with current scrubber technology, i.e. the use of granular soda lime and its method

of packing. Given this constraint, it remains to be seen if the model can produce more efficient replacement schedules.

Unfortunately, the snort data are not available for those contaminants that were measured by real-time monitoring equipment (CO_2, O_2, CO). All real-time data were collected through a datalogger onto a computer file. However, immediately upon completion of the snort, a fire drill training exercise was called and all crewmembers were advised to evacuate the Fore Ends. In haste, the computer was shut down without the file being saved. Attempts to retrieve the data from the datalogger were unsuccessful.

Variation in O_2 concentration

Figure 2 depicts the changes in O_2 concentration in the four main areas of the boat during the 16 hours and 40 minutes monitored. Operational conditions and procedures described for CO_2 also apply to the O_2 monitoring period.

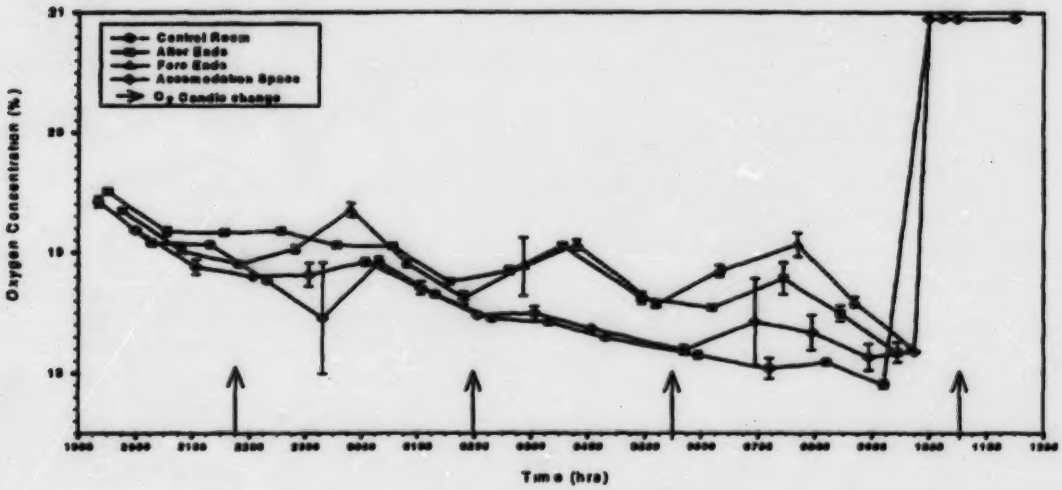

Figure 2. Changes in O_2 concentration and the effects of chlorate candle oxygen generation during patrol state conditions. Single chlorate candles were activated simultaneously in both Fore and After Ends at 2145, 0155, 0548 and 1040 hours.

The observed baseline O_2 concentrations in the four monitored areas indicate that the initial values were well below that of ambient air (20.9%). As described in the previous section, this

simply reflects the fact that 77 personnel had been consuming oxygen for four hours and 45 minutes prior to initiating the monitoring protocol. This resulted in O_2 concentrations of 19.42% in the Control Room; 19.5% in the After Ends; 19.36% in the Fore Ends; and, 19.22% in the Accommodation Space.

As expected, O_2 levels continued to decline until O_2 candles were activated fore and aft at 2145 hours. The replenishment of O_2 varied significantly between compartments. In the Control Room, O_2 actually dropped from 18.97% to 18.84%. In the After Ends, replenishment was slight (from 19.19% to 19.26%), one hour after candle activation. The effect of candle activation was more pronounced in the Fore Ends and Accommodation Space where O_2 levels rose from 18.89% to 19.3% and from 18.82% to 19.08%, respectively.

This pattern of O_2 replenishment more or less repeated itself after each period of candle activation. At no time was candle activation effective in restoring O_2 concentrations in the Control Room and the effect in the After Ends was inconsistent. Only in the Fore Ends and Accommodation Space was there any semblance of consistency in partially restoring the O_2 environment.

Generally speaking, those compartments in which the oxygen generators are situated benefited most from candle activation, i.e. in the Fore Ends and After Ends. The Accommodation Space and Control Room benefited the least. Indeed, despite candle activation, the O_2 levels in the Control Room declined continually, reaching a concentration of 17.9% immediately prior to snorting. As described previously for the removal of CO_2, the blackout curtains appear to curtail any effect that the chlorate candles may have in improving the O_2 in the compartment The deterrence of any dilution effect by the blackout curtains can be seen when the curtains are removed at approximately 0600 hours and the rate of O_2 reduction slows down.

Chlorate candle effectiveness is definitely affected by the positioning of the O_2 generators; the configuration of the various compartments; the lack of exhaust ventilation; the circulation of any enriched air; and, the number of crew occupying a space at any given time.

Over the 21 hours and 38 minutes that the submarine was submerged, O_2 concentrations remained within specifications (18-22%) in all areas except the Control Room. It was only during the last hour, prior to snort, that the Control Room drifted out of specification. It is interesting to note that the O_2 atmosphere was preserved with the consumption of only eight chlorate candles, whereas Standard BR 1326 suggests that 11 to 12 candles would be necessary to maintain O_2 concentrations within specification. This discrepancy can be explained by the fact that candle replenishment occurred every four hours after the initial activation, as opposed to every hour as recommended in the Standard.

Taken at face value, it would appear that preventative steps, taken early in a dive, i.e. the early activation of candles, could preserve the atmosphere. It is also possible, that had the candle replenishment schedule followed the Standard, i.e. every hour versus the four hours observed on this trial, the atmosphere may well have been preserved longer than the 21-hour plus period. This simply points out the fact that the maintenance of the submarine atmosphere is a judgement call of the submarine Commander, based on his experience and his personal interpretation of the Standard.

The weakness in the present approach to submarine air quality management would appear to be in the interpretation of the Standard and the lack of accurate and reliable monitoring systems. With respect to the interpretation of the Standard, it is suggested that it would be useful to bring experienced submarine Commanders together to share their collective experience, both in interpreting and applying the Standard to preserve a habitable submarine environment. Undoubtedly, different Commanders use different strategies. It would be useful to harvest and record this collective experience to assist in developing a new Canadian Standard for submarine habitability. This is particularly true if Canada moves forward with Atmosphere Independent Propulsion (AIP) submarines and the required Atmosphere Independent Life Support (AILS) technologies.

As indicated earlier in the discussion on CO_2 concentrations, it is unfortunate that snort data are not available for real-time monitoring of O_2. The O_2 concentrations seen in Figure 2 after 1000 hours are O_2 values estimated from pre-snort H_2 grab samples. While not accurate, these O_2 concentrations have been added to the graph to identify the inaccuracy and error of detection methods that do not take pressure differentials into account. The current method of measuring O_2, i.e. Draeger tubes, has always been plagued with problems. The conditions onboard (humidity, particulates, interfering gases) make it difficult to obtain an accurate reading at the best of times. Add to this, the inherent error in Draeger tube detection, and one comes to appreciate the magnitude of the problem and the need for some reliable monitoring technology.

In an attempt to overcome the measurement error, many readings were taken with many tubes, over each time period until a consistency of readings was achieved. While this was wasteful and expensive (certainly from an operational perspective), it did provide readings which were relatively reliable and relatively accurate (error ranging from $\pm$ 0.4% to $\pm$ 1.5%). Had single Draeger tube values been used, the error would have been in the 15% - 25% range, as noted earlier.

Variation in CO concentration and resulting COHb changes

Figure 3 shows the changes in CO concentration in the four main compartments of the boat during the 16 hour and 40 minute monitoring period. In order to determine the contributory effect of smoking to the habitability of the submarine, the study did not impose any restrictions on the current smoking policy. To assess the biological effect of CO, representative breath samples from 10 smokers and 10 non-smokers were monitored for COHb. Volunteers were not asked to curtail their habits, only to adhere to their current habits and the policy within the submarine.

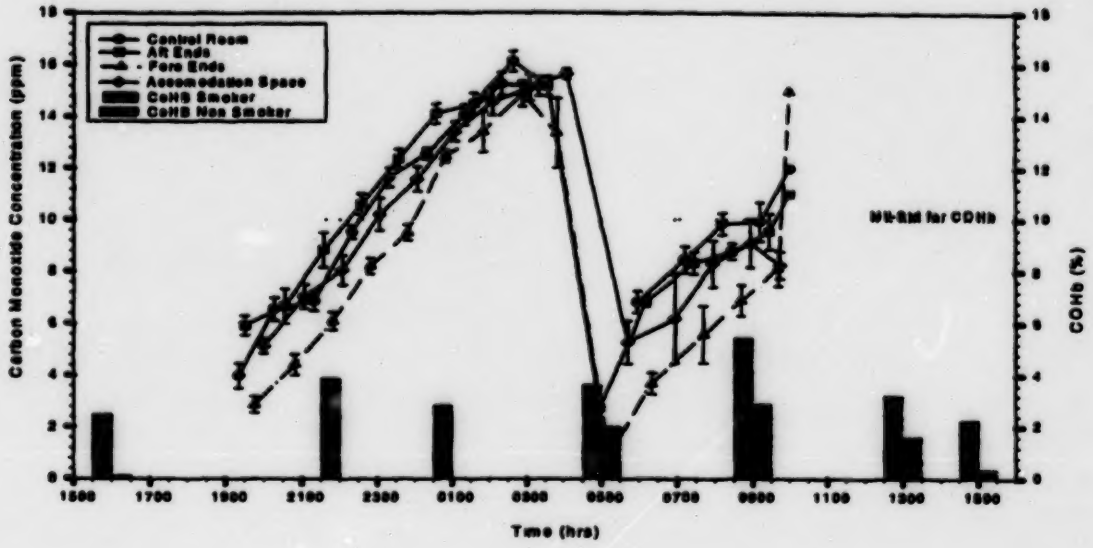

Figure 3. Changes in CO concentration during patrol state conditions and COHb concentrations in representative smokers and non-smokers.

From the time of initial submergence, and the initiation of atmospheric monitoring, CO concentrations increased progressively. This was probably attributable largely to the prevailing smoking policy which permitted smoking in the galley and just forward of Bulkhead 77. Even though smoking was confined to these areas, the poor ventilation throughout the boat basically means that any CO generated, freely diffuses thoughout all compartments. Thus, no single pocket of CO was detected. Instead, the rate of accumulation in each compartment, was relatively the same (2.8 ppm initially in the Fore Ends, peaking at 14.9 ppm; 3.8 ppm to 15.3 ppm in the Control Room; 5.0 ppm to 15.7 ppm in the Accommodation Space; and, 5.9 ppm to16.2 ppm in the After Ends). Cooking fumes also contributed to the CO accumulation but it is impossible to partition out the relative contributions of smoking and cooking. As expected, no existing air purification methodology reduces the concentration of CO.

Figure 3 shows a dramatic decrease in CO in all compartments at around 0400 hours. This is partially attributable to the disconnection of the CO analyzer for re-calibration and the fact that no monitoring was conducted for approximately 30 – 45 minutes. When monitoring re-commenced, the concentration of CO was found to have fallen by 10 ppm. This is attributable, most likely, to the fact that all cooking and baking had ceased and, since

breakfast was in progress, smoking was negligible. From 0600 hours onwards, the rate of accumulation of CO mirrored that observed over the previous 2000 – 0400 hour time frame. At 1040 hours, there was a sudden 5 ppm increase of CO in the Fore Ends. It is believed that this may have been due to incomplete ignition or incomplete and slow burning of the O_2 candle activated in the Fore Ends at that time. Indeed, previous trials performed on Upholder class submarines have found that O_2 candles can malfunction in just this manner [9]. The effect of faulty candles is the release of CO [10]. To address this problem, the UK has developed a canister for absorbing CO. The canister is designed to operate from the Carbon Dioxide Absorption Unit (CDAU) and results have shown that it is capable of maintaining CO concentrations within specifications, at least for the 24 hours over which it was tested [11].

Figure 3 also shows the biological uptake of CO, as measured by COHb. It is immediately apparent that COHb never rose above the Military Standard (Mil.Stand.) of 10% [12] at any time during the monitoring period. The average pre-dive COHb in nonsmokers was 0.2%; in smokers it was 2.4%. These are normal concentrations in such populations. Since COHb can be as high as 6-7% in smokers, the value of 2.4% is indicative of a moderate level of smoking, at least while onboard the submarine. Figure 3 also shows that nonsmokers were affected by secondary smoke (2.0% COHb at 0500 hours and 2.8% at 0900 hours) but that this effect was minor and eliminated completely by snorting.

Since a worse case operational scenario (i.e. an ultra-quiet state) was not observed, it is impossible to predict the potential rise in CO or the effect such a rise would have on nonsmokers and smokers. The results found under patrol state conditions do not indicate a requirement to alter the current smoking policy, but this does not suggest that a change may not be necessary in the future. Further study is required.

Effects of battery charging

To assess the effect of battery charging on the habitability of the submarine, grab samples were taken and analyzed for H_2, Arsine and Stibene. Although H_2 is produced under all battery state conditions, i.e. discharge, open circuit, and charge, it is at the "almost-full charge state", when electrolysis is at a maximum, that the maximum off-gassing of H_2 is likely to occur [1].

The ventilation system within the Battery Compartment of the submarine consists of centrifugal fans which are designed to draw air over the batteries. In harbour, or during surface operations, the exhaust air is discharged overboard. During snorting, air from the battery compartment is discharged through a vent into the engine compartment where it is used by the engines. Because of the ventilation system, the air is also dispersed throughout the boat. For this reason, samples were taken in the Battery Compartment; at the Engine Vent; and, in the Accommodation Space and Control Room.

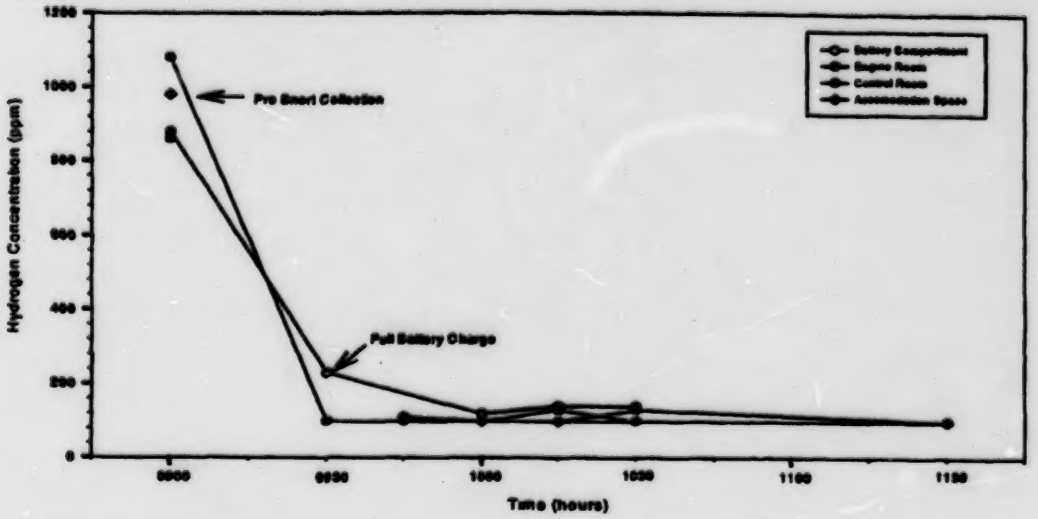

Figure 4. H_2 concentrations: prior to snort; at maximum battery charge; and, two hours after maximum battery charge.

The highest H_2 concentrations were detected immediately before snort but they were well within the 2.0% specification in all compartments. Moreover, H_2 appeared to be distributed equally between compartments. While the highest level was detected in the Control Room (0.11%), this concentration did not differ significantly from that observed in the other compartments (0.1% in the Accommodation Space; 0.09% in the Battery Compartment; and, 0.09% in the Engine Room). Once the full charge state had been reached, H_2 concentrations fell below 0.02% in all compartments.

With respect to the other products of battery off-gassing, i.e. Arsine and Stibene, neither product was detected in any of the monitored areas.

Inhalable airborne particulates

In reviewing past submarine studies on Canadian Oberons [1, 6] and UK Upholders [9, 10,11], it was noted that no attempt had ever been made to analyze for respirable particulates, i.e. those particles which are less than 10 microns in diameter and which can be inhaled into the bronchial tree. Anecdotal reports suggested that aerosolized particulates were a problem and, in discussion with a number of submariners, it was determined that the Engine Room, Motor Room, and Control Room were the most vulnerable areas. As only one monitoring instrument was available, and switching between compartments was not feasible, samples

from each compartment were collected consecutively. The sampling sequence was the Engine Room, Motor Room, and Control Room.

Particulates were monitored over a total period of 23 hours and 48 minutes. The Engine Room was monitored first for a period of seven hours. Monitoring began at 1000 hours, one hour after sailing. During the monitoring period, the submarine transited the surface; dove to an operational depth and remained submerged under non-snort conditions; and, surfaced twice to snort depth (at 1450-1515 hours and 1646-1748 hours) to replenish the atmosphere. Midway through the second snort protocol, the particulate analyzer was moved to the Motor Room, remaining there for three hours and 48 minutes. Finally, the analyzer was moved to the Control Room for the remaining 13 hours of the exercise.

There are no guidelines or specifications covering allowable limits for respirable particulates in Standard BR 1326 or in any Military Standard. Thus, comparisons can only be made with the civilian industrial Standard, the Handbook of the *American Conference of Governmental Industrial Hygienists: Threshold Limit Values for Chemical Substances and Physical Agents* [13]. Figure 5 depicts the actual concentration of particulates measured in each compartment of the submarine over the three sampling periods. The total cumulative respirable particulate concentration in each compartment, in and by itself, should not be interpreted to mean that this was the concentration to which all crewmembers were exposed. As the particulate concentration changes over time within a compartment and between compartments, and as crew members can move freely from one compartment to another, it is most appropriate to present the data as a Time Weighted Average (TWA) exposure over the 23 hour and 48 minute monitoring period. Applying this calculation, the overall TWA exposure throughout the submarine was 0.342 mg/m^3. The TWA exposures in each compartment were 0.677 mg/m^3 in the Engine Room; 0.033 mg/m^3 in the Motor Room; and, 0.214 mg/m^3 in theControl Room.

As stated earlier, there are no military guidelines to dictate allowable respirable particulate concentrations onboard submarines and one must rely upon the civilian industrial Standard [13] governing occupational health exposures. It should be recognized, however, that the industrial Standard applies to an eight-hour day, 40-hour week. These conditions do not apply to submarine operations. Thus, one must interpret the industrial Standard with caution. Recognizing this limitation, the industrial Standard does, however, provide the only available guideline for defining the limits for particulate exposures. Limiting or permissible concentrations are defined as Threshold Limit Values (TLV's). When considered over time of exposure, they are defined as the Threshold Limit Value/Time Weighted Average (TLV/TWA). Under the civilian Standard, generic or unclassified particulates, i.e. those not comprised of silica or asbestos, are defined as falling into two categories: inhalable and respirable. Inhalable particulates (< 10 microns in diameter) are those that can be breathed in and deposited anywhere in the respiratory tract. Respirable particulates are those that can be deposited in the alveolar gas exchange region of the lung. The TLV/TWA is 10 mg/m^3 for inhalable particulates and 3 mg/m^3 for respirable particulates. Since the particle analyzer could not distinguish particle sizes below 10 microns, it is appropriate to apply the TLV/TWA exposure limits for inhalable particulates (10 mg/m^3), while recognizing that this provides a conservative estimate of exposure.

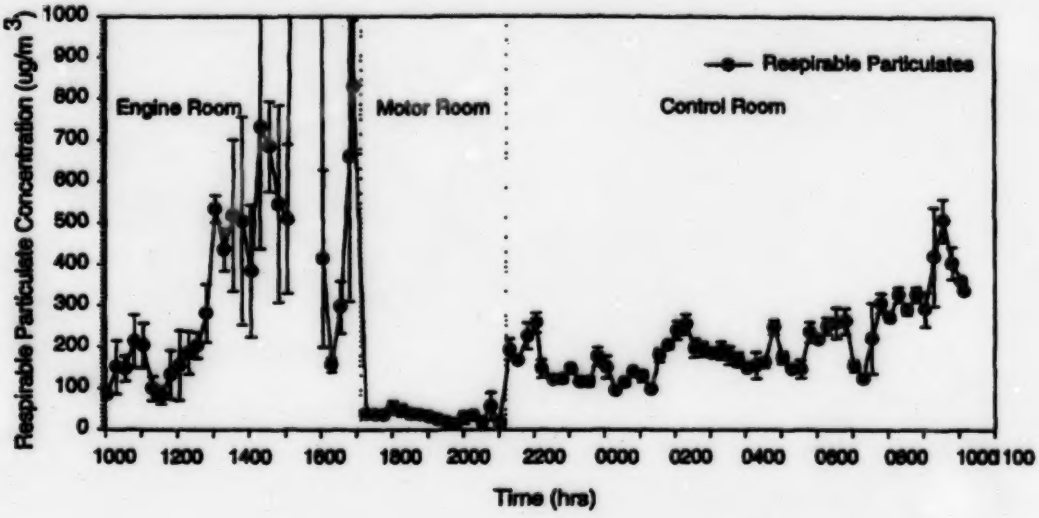

Figure 5. The total inhalable particulates (<10 um) measured consecutively in the Engine Room, Motor Room, and Control Room. Sample points and Standard Deviations are average values determined over successive 10-minute exposure periods.

The overall TLV/TWA of 0.342 mg/m^3 falls well below the industrial limits and thus, at face value, the particulate load in the submarine is acceptable. This assumes, of course, that the particulate material consists of non-toxic, insoluble nuisance particles only. At this time, the composition of the particulate material is unknown. Furthermore, although the TLV/TWA for all compartments fell within industrial limits, peak levels of particulates in the Engine Room did reach 13 mg/m^3 and thus exceeded the Standard. It is concluded that further detailed study of particulates in submarines is warranted, and that future studies should include an analysis of particulate composition. Until this is done, one must reserve judgement as to whether or not the particulate load in a submarine is really acceptable or not.

As previously indicated by Nimmo-Scott [8], many factors must be taken into account when setting any MPC for atmospheric contaminants in a submarine. Risk of exposure, exposure time, toxicity (acute and chronic), biological half-life, and any additive or synergistic effects of other contaminants must be taken into consideration.

Particulate exposure in a submarine could be reduced substantially by installing filters in the ventilation system, although in diesel submarines, it is unlikely that this would reduce the load in the Engine Room itself. It would, however, reduce the overall load throughout the boat. Ideally, such filters should be HEPA filters. These are capable of filtering out bacteria, and thus would have the added benefit of minimizing the spread of any bacterial illness throughout the boat, should such an illness occur. Given the environmental conditions onboard diesel submarines, it is recognized that the introduction of such filters may not be possible, simply because they may become clogged and ineffective in a relatively short period

of time. Nevertheless, the feasibility of installing filters should be investigated and considered in any future submarine air quality management plan.

While uncorroborated at the time of writing this report, it is understood that the Victoria class submarines do have a filtering capacity within their ventilation system. If true, the particulate load in the Victoria's should be substantially less than in the Oberon's. It is recommended that the nature of the filtering system in the Victoria's be investigated, and if HEPA filters are not installed, that an engineering feasibility study be undertaken to investigate their potential installation.

Finally, it should be noted that the introduction of an Atmosphere Independent Propulsion (AIP) system in any diesel submarine should drastically reduce particulate loading. This is based on the belief that the dominant source of particulates is from diesel aerosols. Since the potential AIP fuel source is H_2 and O_2 and the by-products of combustion, water and CO_2; since regenerative monoamine scrubbers appear to be able to eliminate CO_2; and, since the AIP system is essentially closed-looped, it is envisaged that there will be a drastic reduction in the particulate load in AIP submarines.

Other contaminants

Ozone, ammonia and nitrous gases

In order to determine if Canadian submarines were able to meet specifications dictated in Standard BR 1326, it was necessary to monitor not only for the major contaminants of concern (CO_2, O_2, CO), but also potential minor contributing contaminants. NH_4 was measured to determine if gases produced by the sanitary tanks, presented a concern. O_3 was monitored to determine if the electrical instruments posed a problem; and, Nitrous compounds (NO_x, NO, NO_2) were monitored to determine if components of exhaust gases were excessive and posed a problem.

All samples were taken by Draeger tube and all results were found to be below the detection limit of the sampling device ($NH_4 < 5$ppm; $O_3 < 0.05$ ppm; and, Nitrous compounds < 0.5 ppm).

Organic contaminants

Without the capacity to cleanse the air in a submarine, submerged below snort depth, the potential exists for chemicals brought into the submarine, and/or any chemical products inherent to the construction of the submarine, could off-gas and accumulate. Having no knowledge of the number of such compounds present onboard HMCS Okanagan, or their quantities, atmospheric samples were collected on both charcoal adsorption media and thermal desorption media as described under Methods. In collecting on both media, it was hoped that a relatively accurate fingerprint of the organic compounds present could be determined. The term 'relatively accurate' is intentional, simply because of sampling limitations. If one knows what contaminants are present, one can selectively analyze for them. If one does not know, it becomes a 'best guess' situation, based upon expectations of

the chemicals present; an estimate of what compounds will be adsorbed on what sampling material; an anticipated concentration level of such compounds, over time; and, an estimate of their breakthrough concentrations on the chosen adsorbents, i.e. the concentration at which the adsorbent becomes saturated. These comments are included as a cautionary note to emphasize the fact that not all chemical compounds were necessarily captured by the method of sampling, nor were the concentrations of the various chemicals, necessarily accurate. By that, it is meant that the measured concentrations represent the *minimal* concentrations of each chemical. Values may well have been higher, depending on their individual breakthrough characteristics on the adsorbents.

With this caveat, it can be stated that the charcoal tube sampling protocol did produce accurate results, since the quantities of diesel effluent could be accurately determined. Table 1 shows the concentrations of the primary organic compounds found in diesel effluent, as determined from the charcoal tubes. These compounds were selected for analysis because they are known components of diesel fuel and are listed as contaminants in Standard, BR 1326.

Table 1. Total accumulation of primary diesel effluents found in the Accommodation Space, Control Room, Fore Ends, and Engine Room during 20 hours under patrol state conditions.

COMPOUND				
Benzene	0.087	0.178	0.129	0.249
Toluene	0.562	0.535	0.537	1.145
Ethylbenzene	0.088	0.191	0.165	0.158
m/p-Xylene	0.282	0.861	0.729	0.782
o-Xylene	0.122	0.359	0.305	0.282

A cumulative concentration over the 20-hour observance period indicated that all diesel components were within specifications [1]. For all compounds, the highest levels were observed in the Engine Room and in the Galley. Excluding benzene, which is found almost exclusively in fuel and rarely in other products, the other three compounds are heavily used as solvents. Toluene is found in paints, coatings, oils, resins, adhesives, and detergents to name but a few; Xylene contains approximately 20% Ethylbenzene, and besides being a component of fuel, is found in many petroleum products such as paint solvents, alkyl resins and rubber cement [14]. Therefore, their presence in areas of the boat where fuel is not combusted, could be attributed to a simple dilution/distribution effect throughout the boat and/or to the use of petroleum products such as cleaning solvents and degreasers. Regardless, all chemical components remained within specifications.

This was confirmed by the Mass Spectrometric results of the compounds identified by a 'best-fit' to the Mass Spectral library of unknown compounds. In this analysis, an 80% match between the chemical detected, and that contained within the library, was selected. Applying this criterion, 30 such compounds were identified and their concentrations are shown in Table 2. Almost all of the volatile organic compounds were found to be diesel fuel aliphatic hydrocarbons or fractions from petroleum products used as fuels, solvents, and cleaners [16,17]. Their presence, neither novel nor uncommon [3, 6, 15], suggests a longstanding problem and it is contended that the problem could be alleviated or reduced by installing activated charcoal filters, in-line in the ventilation system. As in the case of the recommendation for particulate filters, it is not known if this is either practical or feasible. An engineering feasibility study to examine the problem would provide an answer and should be carried out.

Table 2. Fingerprint identification of contaminants present onboard during patrol state conditions. Contaminants identified by mass spectrometry. Only those compounds with a greater than 80% match to the spectral library, were identified.

COMPOUND				
Dichlorodifluoromethane Freon -12	277.8	328.9	241.2	46.0
Cyclohexane	15.2	16.4	4.5	8.4
Heptane	15.4	27.6	17.4	26.4
Methylcyclohexane	53.6	28.6	20.5	28.6
cis-1,2-Dimethylcyclohexane	2.3			
cis-1,3-Dimethylcyclohexane		20.5	10.6	
trans-1,2-Dimethylcyclohexane		6.3		
trans-1,3-Dimethylcyclohexane	1.4		3.3	8.8
trans-1,4-Dimethylcyclohexane	4.1			
2-Methylheptane	12.3	34.8	25.4	21.2
3-Methylheptane			6.3	
4-Methylheptane		2.3		3.24
2-Methylhexane	2.8	7.4		

Table 2 continued

Concentration				
3-Methylhexane	3.8	7.1	7.1	
Dimethylcyclohexane	5.3	13.9	7.3	23.7
1,3-Dimethylcyclohexane	6.2			
Tetrachloroethene	2.9			
Octane	14.7	6.2	10.1	35.5
(1-Methylethyl)-cyclohexane				1.0
2-Methyloctane		7.4		19.5
Ethylcyclohexane	10.4	18.9	18.2	25.5
1,1,3-Trimethylcyclohexane		6.7	4.2	6.1
Propylcyclohexane	1.7	7.3		9.8
(1-Methylethyl)-benzene				3.1
trans-1,3-Dimethylcyclopentane	1.4			
Decane	17.6	30.7	24.5	41
Butylcyclohexane		2.3		3.7
l-Limonene	4.2	9.8	7.0	8.2
Undecane	2.3	2.9		7.4
trans-1-Ethyl-4-Methylcyclohexane		2.4		5.1
Trimethylcyclohexane	0.6			
1-Ethyl-3-methylbenzene			3.2	
Trans-Decahydro-naphthalene				4.4

Even though all compounds were found to be well below specifications, exposure to aromatic hydrocarbons is always a cause for concern. At best, they are irritants; in-between, they can produce narcotic effects at high levels (15); and, at worst, they may be carcinogenic (13). Whether they are simply irritants or carcinogenic, they present health hazards to the crew. For this reason, it is essential that some method of identifying their presence be brought into the submarine.

Assessment of a potential new CO_2 detector

During this trial, a potential replacement CO_2 analyzer (Guardian Plus Model D400 Infrared, Edinburgh Sensors Ltd., Livingston, England) was evaluated. It was placed in the Fore Ends over the entire monitoring period and was found to produce very comparable results to the DCIEM analyzer used in the study. Not surprisingly, it was also found to be much more reliable than the Draeger technology used currently. The IR method of detection is proven and reliable and the cost of the instrument is reasonable ($3000.00).

The disadvantage of the instrument is that it only operates on AC power. Thus, while described as being portable, it is only portable if it can be conveniently moved and plugged into an AC power source. During this trial, the instrument was not unplugged, moved, and then plugged in again, so one cannot comment on the stability of the instrument under such conditions, i.e. its warm-up time after being unplugged and plugged in many times or its ability to remain within calibration. If the instrument could not tolerate such movements, the only solution would be to leave it connected in critical compartments to be monitored. This would require multiple monitors in an environment with very limited space, so this might not be an option. If a switching valve and sampling lines could be installed throughout the boat to permit sampling in the various compartments, a single instrument could be installed in whatever location offered the most available space.

As well, the manufacturer suggests that calibration is only necessary every three months. It was found, however, that more frequent calibration was necessary in order to obtain accurate measurements. If the instrument were to be adopted for submarine use, it is recommended that a calibration be performed prior to each departure and upon return. At sea, calibration may not be feasible since certified gas standards (compressed gas cylinders) are required for calibration and their storage may be a problem. Thus, for a number of reasons, this monitor may not be an acceptable alternative to the Draeger system.

While this instrument may not be acceptable, it is a relatively portable IR detector and it can withstand the harsh submarine environment and provide accurate and reliable results. What is really required is a battery-operated, portable IR CO_2 detector with an internal electronic calibration feature. It is not known if such an instrument is on the market.

Recommendations

The following recommendations are made, based upon the findings of this study and taking into consideration the upcoming acceptance of the Victoria class submarines.

1. With the difficulty in retrieving UK reports and documents regarding environmental testing of the Upholder submarine (even though requests have been made through appropriate official channels) it is recommended that the need for this documentation be included in the SOR for the Victoria purchase and exchange/training. Documentation of air quality findings and the recommendations to improve conditions would be invaluable. Studies would not have to be performed twice; previous inefficiencies could be reviewed; and, any worthwhile recommendations made previously by the RN, with respect to changes in policies and procedures, could be implemented.

2. To make the most efficient use of the CO_2 canisters that are available for routine use onboard submarines, it is crucial that recommendations suggested by Nimmo-Scott be re-examined; criteria for calculations confirmed; canister replacement efficiency reviewed; and, a replacement schedule provided.

3. The current method of detecting and quantifying contaminants (Draeger tubes) is very unreliable, expensive and inaccurate. With the ensuing acceptance of the Victoria's, commercially available instruments should be critically examined for suitability in the unique and harsh environment of the submarine. Although the criteria for acceptability is stringent, renting equipment for trial purposes, or having distributors loan the equipment would allow modifications to be made (humidity control, pressure compensator, inlet filter) to adjust equipment to meet the needs of the environment. It would be almost impossible to simulate conditions onboard a submarine; thus, it should be considered mandatory that any potential detection device be tested while the submarine is at sea.

4. The design of the UK-developed CO absorption canister that can be used in the CDAU's should be investigated. Canada should invest in any method for removing CO which has proven successful and will improve the habitability of the submarine.

5. Knowing that there are considerable particulates present onboard a submarine, it would be prudent to investigate collective devices which could be attached to the ventilation exhaust system prior to circulating air throughout the boat. It is understood that the Victoria class has such a filter system, although this cannot be corroborated. If at all possible, taking into account engineering design limitations, a HEPA filter capable of preventing bacteria from circulating, would be ideal. As well, Volatile Organic Compounds (VOC's), which circulate throughout the boat, could probably be removed or reduced by installing activated charcoal filters. It is recommended that engineering feasibility studies be carried out to investigate the possibility and practicality of installing the above filters.

6. DND's devolvement of funds to the Unit level, for the local procurement of supplies, has resulted in local purchases of materials for submarines (solvents, cleaning agents etc.). Although likely cost- and time-efficient, this manner of purchasing has and can result in products being brought onboard that are potentially toxic. All items, intended for purchase and use on submarines, should be reviewed for their toxicity, prior to purchase. This can be done by examining the individual Material Safety Data Sheets (MSDS's). A guideline, similar to the Royal Navy's BR 1326 (A), *Materials Toxicity Guide* [18] should be implemented. All materials introduced to the submarine should be recorded, and their toxicity and conditions for use, noted. Introducing such a Guide would enhance awareness of toxicity issues amongst end-users, managers and policy advisors, alike. It would also introduce consistency between boats and, above all, reduce unnecessary exposure of the crew to potentially harmful compounds.

7. As operational training requirements took priority over the original protocol conditions for this study, a worse case atmospheric condition, i.e. the ultraquiet state, was not observed. To determine the maximum level of contaminants that may be present; assess the risk of exposure; examine compliance with Standards; and, if necessary, advise on changes in SOP's to improve atmospheric conditions, it is necessary to re-evaluate submarine air quality in scenarios which would include the ultraquiet state. Ideally, a study that monitored air quality in *all* possible operational scenarios would provide the results needed to guide the Navy in maintaining atmospheric quality onboard a submarine. It would also assist in the development of an atmosphere monitoring policy; provide evidence of the effects of smoking; guide the establishment of a submarine smoking policy; and, assist with the development of air purification procedures for smoke clearance and other emergencies.

8. Sole adoption of Standard BR 1326 [1], and the resulting loss of replacement schedules for CO_2 canisters and O_2 candles contained in the previous Standard BR 3944 [7] has resulted in guidelines being open to interpretation in certain situations. Undoubtedly, different strategies are used by different submarine Commanders to monitor and maintain the environment. It is recommended that experienced submarine Commanders be brought together to share their collective experience in both interpreting and applying the Standard in preserving a habitable submarine environment. It would be useful to harvest and record this collective experience because Canada could develop and adopt its own Standard for submarine habitability. This is particularly true if Canada is to move forward with Atmosphere Independent Propulsion (AIP) submarines and the required Atmosphere Independent Life Support (AILS) technologies.

References

1. Air Purification in "O" Class Submarines. Royal Navy Standard BR 1326 (OOS), 1988.

2. Submarine Air Quality Management Initiatives. File 10081-1 (N00 Comd.), 26 January 1998.

3. An Air Quality Assessment Onboard an "Oberon" Class Submarine – HMCS Okanagan. DCIEM Report No. 87-RR-28, 1987.

4. Minutes to the Submarine Air Quality Initiative Pre-planning Meeting - HMCS Okanagan. File 10081-1 (N37-7 Subs OT & E), 20 April 1998.

5. NIOSH Manual of Analytical Methods. 4th Edition. U.S. Department of Health and Human Services. National Institute for Occupational Safety and Health. Cincinnati, Ohio, 1994.

6. Air Quality in "Oberon" Class Submarines [2] - An Assessment Onboard HMCS Onondaga. D.Kane and D. B. Van Loon. Unpublished DCIEM Report, 1990.

7. Air Purification in Patrol Class Submarines. Royal Navy Standard BR 3944, 11/1978.

8. A Study of Atmospheric Control in Patrol Submarines in the Royal Navy. W. Nimmo-Scott. Report to Flag Officer, Submarines,1981.

9. Sea Acceptance Test, Air Purification Test Form for Conventional Submarines - HMS Upholder. RN-SSCF72, 1990.

10. Sea Acceptance Test, Air Purification Test Form for Conventional Submarines - HMS Unseen. RN-SSCF72, 1992.

11. Sea Acceptance Test, Air Purification Test Form for Conventional Submarines - HMS Ursula. RN-SSCF72, 1994.

12. Human Factors Engineering Design for Army Material. MIL-HDBK-759A, July 1987.

13. American Conference of Governmental Industrial Hygienists - Threshold Limit Values for Chemical Substances and Physical Agents. ACGIH, Cincinnati, Ohio, 1999.

14. American Conference of Governmental Industrial Hygienists - Documentation of the Threshold Limit Values and Biological Exposure Indices. ACGIH, Cincinnati, Ohio, 1996.

15. Submarine Atmosphere Control and Air Purification. F. J. Raffaelli. INM Report No. 21/88, 1988.

16. Clinical Toxicology of Commercial Products. 5th Edition. Williams and Wilkins, Baltimore & London, 1984.

17. The Merck Index. 12th Edition. Merck & Co. Inc., Rathway New Jersey, 1996.

18. Materials Toxicity Guide. Royal Navy Standard BR 1326 (A), 1990.

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14. ABSTRACT

(U) Prior to the Canadian Navy's move to the new Victoria class submarine (former RN Upholders), DCIEM was tasked to re-examine the air quality on an Oberon class submarine to determine if the atmosphere complied with Air Purification Standard BR 1326. The objective of the study was to obtain information to assist in developing plans for future submarine air quality management. Since the information would be directly applicable and transferable to the Victoria submarines, the conduct of a trial on an Oberon was warranted. This trial represents a baseline evaluation of submarine air quality under patrol conditions. Over a 24-hour period, the functional and detection capabilities of analytical instruments for monitoring the atmosphere were assessed and a 'fingerprint' of the contaminants onboard was obtained. A profile of Carbon Dioxide (CO2) accumulation and Oxygen (O2) consumption was determined and the effectiveness of air purification (CO2 scrubbing; O2 generation, and, snorting) was assessed. In addition, Carbon Monoxide (CO) was monitored and Carboxyhemoglobin (COHb) was measured in representative smokers and nonsmokers. Ammonia (NH4), Ozone (O3), and Nitrous compounds (NOx) were measured to assess, respectively, whether the sanitary systems, electrical systems, and engine exhaust gases posed any problems. Hydrogen (H2), Arsine, and Stibene were monitored to assess any potential hazard from charging the batteries. To assess the health hazard potential of aerosolized particles derived from cooking, smoking, and diesel fuel & exhaust gases, concentrations of respirable airborne particulates were measured. All contaminants covered by BR 1326 were found to be within allowable limits. Respirable particulates are not covered by BR 1326, nor by any other Military Standard, and the data were interpreted by applying the Threshold Limit Value/Time Weighted Average (TLV/TWA) civilian occupational health guidelines. The overall TLV/TWA for particulates was within allowable limits. Despite the fact that CO2 and O2 concentrations fell within acceptable limits, the study confirmed that air purification measures on diesel submarines are minimal and poorly placed and that there is a lack of exhaust ventilation. Poor to non-existent air exchange was compounded by compartmentalization and blackout curtains; and, contaminant measurement devices (mechanical colorimetric analyzers) were confirmed to have inherent measuring errors. A review of management practices revealed that the adoption of BR 1326, as the sole submarine air purification Standard, had resulted in the loss of replacement schedules for CO2 canisters and O2 candles contained in a previous Standard, BR 3944. Moreover, the guidelines to assist Commanders in maintaining air quality in submarines appear to be open to interpretation. Although atmospheric conditions were found to be within specifications, several recommendations are made to enhance the management of submarine air quality in Victoria class submarines.

Avant que la Marine canadienne ne commence à utiliser les nouveaux sous-marins de classe Victoria (d'anciens sous-marins de type Upholder de la RN), on a confié à l'IMCME la tâche de reexaminer la qualité de l'air à bord d'un sous-marin de classe Oberon, afin de déterminer si l'atmosphère est conforme à la norme d'épuration de l'air BR 1326. L'objectif de l'étude était de recueillir des renseignements permettant de faciliter l'élaboration de futurs plans de gestion de la qualité de l'air à bord de nouveaux sous-marins. L'exécution d'un essai à bord d'un Oberon est justifiée puisque les renseignements obtenus peuvent être directement appliqués et transférés au cas des sous-marins de classe Victoria. Cet essai correspond à une évaluation de référence de la qualité de l'air d'un sous-marin dans des conditions de patrouille. On a évalué, au cours d'une période de 24 heures, les capacités de fonctionnement et de détection d'instruments d'analyse servant à contrôler l'atmosphère et on a déterminé « l'empreinte chimique » des agents contaminants présents à bord. On a établi un profil de l'accumulation de dioxyde de carbone (CO_2) et de la consommation d'oxygène (O_2) et on a évalué l'efficacité du système d'épuration d'air (épuration du CO_2, production d'O_2 et marche au schnorchel). De plus, on a surveillé la concentration de monoxyde de carbone (CO) et mesuré celle de carboxyhémoglobine (COHb) dans le sang de fumeurs et de non-fumeurs représentatifs. On a mesuré les concentrations d'ammoniac (NH_4), d'ozone (O_3) et de composés azoteux (NO_x) afin de déterminer si ces gaz, associés respectivement aux circuits sanitaires, aux circuits électriques et aux systèmes d'échappement des moteurs, créent des problèmes. On a surveillé la concentration d'hydrogène (H_2), d'arsine et de stibine afin d'évaluer tout danger pouvant résulter de la charge de batteries. Afin d'évaluer les dangers potentiels pour la santé que posent les particules en aérosol provenant de la cuisson, de l'usage du tabac et des gaz d'échappement et de carburant diesel, on a mesuré les concentrations de particules atmosphériques inhalables. Les concentrations de tous les contaminants dont traite la Norme BR 1326 se situent dans les limites acceptables. La Norme BR 1326, ou toute autre Norme mesure, ne traite pas des particules inhalables. L'interprétation des données relatives à ces substances a donc été effectuée en appliquant la valeur limite d'exposition (TLV) et l'exposition moyenne pondérée en fonction du temps (TWA) des lignes directrices civiles en matière de santé professionnelle. Les valeurs globales de TLV et de TWA, pour les particules, se situent dans les limites acceptables. Bien que les concentrations de CO_2 et d'O_2 se situent aussi dans les limites acceptables, l'étude a confirmé que les mesures d'épuration de l'air, dans les sous-marins à propulsion diesel, sont manuelles et mal situées et que la capacité de la sorbe de vaporisation n'est pas suffisante. Le renouvellement d'air est inexistant ou minon, de qualité médiocre, et le problème est aggravé par la compartimentation et les réseaux d'occultation. On a aussi confirmé que les appareils utilisés pour mesurer la concentration des contaminants (des analyseurs colorimétriques mécaniques) possèdent des erreurs de mesure intrinsèques. L'examen des pratiques de gestion révèle que l'adoption de la Norme BR 1326 comme norme exclusive en matière d'épuration de l'air à bord des sous-marins a entraîné l'élimination des remplacements périodiques de réservoirs filtrants de CO_2 et de bougies filtrantes pour O_2, lesquels faisaient partie d'une norme antérieure (BR 3944). De plus, les lignes directrices visant à aider les Commandants à assurer la qualité de l'air dans les sous-marins semblent être l'objet de différentes interprétations. Bien qu'on ait établi que les conditions atmosphériques se situent dans les normes, nous proposons plusieurs recommandations visant à améliorer la gestion de la qualité de l'air à bord des sous-marins de classe Victoria.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Oberon; diesel submarines; submarine air quality; submarine atmospheric monitoring